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HARVESTING SYSTEM SUSTAINABILITY IN MEDITERRANEAN OLIVE CULTIVATION: OTHER PRINCIPAL CULTIVAR

Bruno Bernardi[1], Giacomo Falcone[1], Teodora Stillitano[1], Souraya Benalia[1]*, Jacopo Bacenetti[2], Anna Irene De Luca[1]

[1]Dipartimento di Agraria, Università degli Studi Mediterranea di Reggio Calabria, Località Feo di Vito, 89122 Reggio Calabria, Italy

[2] Dipartimento di Scienze e Politiche Ambientali, Università degli Studi di Milano, Via Celoria, 2, 20133 Milano, Italy

*Correspondence author: soraya.benalia@unirc.it

Abstract

In the olive production sector, which is increasingly expanding beyond the borders of the Mediterranean basin, harvesting is the most demanding phase from both an economic and organisational point of view. Traditional olive orchards are still predominant, with centuries-old and large plants, and are characterised by the gradual ripening of drupes and irregular planting patterns. Even though the structural conversion of these olive orchards into more modern cultivations may be difficult owing to their historical, monumental, and landscaping importance, as well as the existing legal restrictions, supporting a "modernisation" process aimed at mechanising the main farming operations remains a priority. Technological innovation is, therefore, a primary objective for Mediterranean olive growing, as well as the enhancement of its strengths. The present study aimed to assess different olive harvesting sites, considering the technical, economic, and environmental aspects to develop a better version of the "olive harvesting database". The applied methodology, also called the "modular approach", represents a useful tool for application in unitary process assessment to obtain a comprehensive database of diverse agricultural operations. Eight olive harvesting systems were compared: six highly mechanised scenarios, one based on mechanical-aided harvesting, and the final one based on fully manual harvesting. The mechanised systems obtained a better performance in terms of working capacity, as only 3.5 h ha^{-1} were needed to harvest 12 tonnes using a self-propelled trunk shaker. In addition, the economic results revealed that mechanical harvesting, diversely from manual or aided harvesting, is the only way to decrease production costs. From an environmental point of view, manual and mechanical-aided harvesting showed the best performance in terms of impact per hour. However, using the mass-based unit (one kilogramme of harvested olives), the results were the opposite and this could be very relevant for the ecoprofile of olive oil.

Keywords

Machinery, Modular life cycle assessment (LCA), Olive harvesting, Production costs, Technical performance

1. Introduction

Olive groves are spread over 10.6 million ha worldwide. Mediterranean region on its own produces about 84% of the world's olives and 97% of the global virgin olive oil. Indeed, 24% of olive harvested area is located in Spain and 11% in Italy (FAOSTAT, 2016). Calabria (Southern Italy) is the second largest olive oil producer with over 184,000 ha of olive groves and a production of more than 126,000 tonnes of oil per year (ISTAT, 2017). Its olive orchard patrimony is characterised by high variability owing to the co-existence of extensive orchards with few trees per hectare and intensive orchards containing more than 600 trees per hectare.

Traditional orchards management is often based on old habits, such as training olive tree according to a three or four branched vase system, which, due to the 10-year pruning frequency, tends to assume a “free form” and may provide high product quantities. While, in intensive orchards whose productivity is also influenced by the mechanisation level they are subject to, we often assist to an improper organization, compromising thus, the orchard potential production.

Approximately 88% of olive farms are less than 5 ha in size, and among these more than two-thirds are less than 2 ha, with farming lands composed of hilly and mountainous areas for greater than 88% of their surface (ISTAT, 2010). These conditions determine a very low probability for investments in the most widespread technologies.

Production in these regions is characterised by a high percentage of lampante oil production; however, we are assisting in the last years to the increasingly improvement of oil quality. Indeed. Good quality olive oil can be obtained even from older groves using adequate harvesting techniques (Almeida & Peça, 2012; Bernardi et al., 2016; Vieri & Sarri, 2010).

The conversion of these orchards into new intensive ones is limited owing to their historical, monumental, and landscaping importance, as well as the limitations caused by the existing regulations (Famiani et al., 2014); however, it is possible to enhance many existing orchards using machinery, such as pneumatic combs and trunk shakers, which can make these orchards more sustainable, both from productive and economic point of view. The importance that harvesting phase has in olive growing has been shown in previous studies undertaken on machines and work sites, which have been aimed at investigating different aspects, e.g. data regarding operational working time and work experience were collected by Famiani et al. (2014); studies on vibration frequency, acceleration, and duration transmitted by trunk shakers to plants were performed by Leone et al. (2015) and Sola-Guirado et al. (2014, 2018). In addition, new materials and harvesting machines have been tested by Bernardi et al., (2018b) and Sola-Guirado, Ceular-Ortiz, and Gil-Ribes (2017).

Harvesting in olive growing, however, is experiencing a period of a new attention toward the technologies to be applied. In the last years the establishment of super-intensive olive orchards has favoured the development of straddle harvesters able to work in these orchards (Giametta et al., 2010). The objective is, on one hand, to increase the number of trees per hectare to realize a continuous harvesting, and on the other hand to guarantee an alternative to trunk shaker or mechanical-aided harvesting in intensive or traditional olives orchards. In this sense, canopy shakers offer the possibility to increase field capacity in terms of harvested hectares per hour (Sanders, 2005). As reported by Savary et al. (2011), these machines have a main configurations characterised by a lateral single-row harvester, with the function to establish the contact between beating rods and bearing branches, equipped, in self-propelled version, with a catch frame equipped with several interceptive conveyor belt.

In the olive orchard trained according to the “monocone” shape, it is possible to realise the harvesting by self-propelled machines such as the side-by-side type. It consists of two machines with sloping padded frames, which traverse each side of a tree row being harvested. One machine has a shaker head located beneath the catching frame. This one overlaps the tree trunk and delivers fruit to a conveyor system carried on the other machine which also consists of elevator, blower and bin or bulk carrier (Ravetti & Robb, 2010; Zion et al., 2011).

In addition, many recent technological innovation could allow a more widespread application of robotics in the sector, in the short to mid-term. This is, furthermore, supported by the availability of a low-cost technology, which responds to the needs of the current new agriculture based on precision, data sharing, rapid availability of timely information and communication; e.g. Miglietta et al., (2019) assessed the sustainability of olive orchard planting management of different olive fruit-harvesting methods on the basis of the data collected thanks to the Geographic Information System.

However, despite many on-going developments at the experimental stage, olive harvesting is having little automation for various reasons, among which, the difficulty of obtaining standardized orchard categories that adapt the crop to the machine, or fitting the machine to the crop as reported by Colmenero-Martinez et al., (2018).

Previous studies have also been undertaken on harvesting cost assessments. For example, Cicek (2011) analysed the costs of four different harvesting methods in Turkey and Zipori *et al.* (2014) compared four harvesting methods applied to four different cultivars in Israel by evaluating the technical, economic, and qualitative efficiencies. Similar studies were performed by Bernardi et al. (2018a) and Mansour et al. (2018) who analysed in-depth specific harvesting methods.

Beside the above mentioned aspects, the awareness toward environmental sustainability is continuously arising. Life cycle assessment (LCA) is considered as the most effective methodology for assessing the environmental sustainability of a process or product. LCA is characterised by the expansion of the analysis boundaries to the whole life cycle of a product or process, in a so-called cradle-to-grave approach. Numerous applications of this method regarded olive and olive oil production, such as those performed by Guarino et al. (2019); Notarnicola et al. (2013); Pattara et al. (2016); Salomone et al. (2015) and Tsarouhas et al. (2015). In some studies, LCA has been jointly performed with economic analysis (De Gennaro et al., 2012; De Luca et al., 2018; Mohamad et al., 2014; Notarnicola et al., 2004) as well as social evaluations (De Luca et al., 2018) using the same methodological framework as the LCA to achieve an integrated sustainability assessment (Table 1). One of the main issues making the application of LCA both time consuming and expensive is the requirement for large amounts of quality data regarding technological, temporal, and geographical representativeness (ISO 14040:2006; ISO 14044:2006).

Table 1. *Analysis of literature*

Authors	Year	Journal	Title	Methodologies applied	Functional unit	System boundaries	Main results
Notarnicola, B., Tassielli, G., Nicoletti, G.M.,	2004	New Medit	Environmental and economical analysis of the organic and conventional extra-virgin olive oil.	Life Cycle Assessment and Life Cycle Costing	1 kg of Extra virgin olive oil	cradle-to-oil mill gate	Organic olive oil scores worse than the conventional both from environmental and costs point of view. The accounting of external costs makes organic oil less expensive
De Gennaro, B., Notarnicola, B., Roselli, L., Tassielli, G.	2012	Journal of Cleaner Production	Innovative olive-growing models: an environmental and economic assessment.	Life Cycle Assessment and Life Cycle Costing	1 ton of olives	cradle-to-farm gate	High Density Olive Grove Systems obtained better performance both from environmental and economic side than Super High Density Olive Orchards
Notarnicola, B., Tassielli, G., Renzulli, P.A.	2013	Proceedings Conference "VII Scientific Conference of the Italian LCA Network"	The variability of data in the LCA of olive production (In Italian)	Life Cycle Assessment	1 kg of olives	cradle-to-farm gate	High variability was found on the eco-profiles of 63 analysed farms. The processes that most influence environmental performance are fertilisation and phytosanitary treatments.
Mohamad, R. S., Verrastro, V., Cardone, G., Bteich, M. R., Favia, M., Moretti, M., & Roma, R.	2014	Journal of Cleaner Production	Optimization of organic and conventional olive agricultural practices from a Life Cycle Assessment and Life Cycle Costing perspectives.	Life Cycle Assessment and Life Cycle Costing	1 ha of cultivated surface	cradle-to-farm gate	Organic cultivation of the olive tree allows for lower environmental impacts and higher profits
Salomone, R., Cappelletti, G.M., Malandrino, O., Mistretta, M., Neri, E., Nicoletti, G.M., Notarnicola, B., Pattara, C., Russo, C., Saija, G.	2015	Life Cycle Assessment in the Agri-food Sector Case Studies, Methodological Issues and Best Practices, Springer Publishing	Life Cycle Assessment in the Olive Oil Sector	Review	-	-	72 studies on the application of life cycle methodologies to the olive oil sector were analysed
Pattara, C., Salomone, R.,	2016	Journal of Cleaner Production	Carbon footprint of	Carbon Footprint of	5 l of Extra virgin	cradle-to-oil	Fertilization represents

Cichelli, A.			extra virgin olive oil: a comparative and driver analysis of different production processes in Centre Italy	Product	olive oil	mill gate	ever the biggest impact contributor followed by plant protection treatments
Tsarouhas, P., Achillas, Ch., Aidonis, D., Folinas, D., Maslis, V.	2018	Journal of Cleaner Production	Life Cycle Assessment of olive oil production in Greece.	Life Cycle Assessment	1 l of Extra virgin olive oil bottle	cradle-to-oil mill gate	Olive cultivation, olive milling and bottle production are the biggest hotspots
De Luca, A.I., Stillitano, T., Falcone, G., Squeo, G., Caponio, F., Strano, A., Gulisano, G.,	2018	Chemical Engineering Transactions	Economic and Environmental Assessment of Extra Virgin Olive Oil Processing Innovations	Life Cycle Assessment and Life Cycle Costing	0,75 l of Extra virgin olive oil bottle		The use of calcium carbonate during olive oil milling allows to reduce the milling time and getting so better performance in terms of environmental and economic impacts
De Luca, A.I., Falcone, G., Stillitano, T., Iofrida, N., Strano, A., Gulisano, G.	2018	Journal of Cleaner Production	Evaluation of sustainable innovations in olive growing systems: A Life Cycle Sustainability Assessment case study in southern Italy.	Life Cycle Assessment, Life Cycle Costing, Social Life Cycle Assessment, MCDA, LCSA	1 ha of cultivated surface	cradle-to-farm gate	Weeding with low-dosage/no-tillage allows the better sustainability performance respect to conventional or mechanical weeding
Bernardi, B., Falcone, G., Stillitano, T., Benalia, S., Strano, A., Bacenetti, J., De Luca, A.	2018	Science of the Total Environment	Harvesting system sustainability in Mediterranean olive cultivation.	Work Productivity Assessment, Life Cycle Assessment, Harvesting cost methodology	1h harvesting operation, 1 ha of olive grove harvested, 1 kg of olive harvested	only harvesting process	Mechanical harvesting of olives allows to obtain the best performance in technical, economic and environmental terms
Guarino, F., Falcone, G., Stillitano, T., De Luca, A.I., Gulisano, G., Mistretta, M., Strano, A.	2019	Journal of Environmental Management	Life cycle assessment of olive oil: A case study in southern Italy.	Life Cycle Assessment	0,75 l of Extra virgin olive oil bottle	cradle-to-oil mill gate	Innovative oil milling technology allows reduction of environmental impacts

Considering the previously reported aspects, the present research aims to I) evaluate the technical efficiency of different harvesting scenarios and their influence on the resulting oil quality and to define their different environmental and economic performances; and II) expand the knowledge on olive harvesting by using a database of harvesting scenarios, considering the harvesting module as a stand-alone life cycle to make the obtained results applicable in other contexts, following Bernardi et al. (2018a) who aimed at building a database about olive harvesting, for the collection and integration of the results.

Recently, many studies that applied the LCA have focused on the analysis of only one process (Lovarelli et al., 2016; Lovarelli and Bacenetti, 2017) through the application of a “gate to gate” approach. Focusing the LCA on a single process does not limit the integration data and produces life cycle studies that have wider boundaries. In practice, this type of approach, the so-called “modular approach” (Bernardi et al., 2018a; Buxmann et al., 2009; Cerutti et al., 2014; Jungbluth et al., 2000), allows the construction of an open source database for the scientific community. Specific processes, which are generally not modelled within commercial databases such as Ecoinvent® or Agrifootprint®, are analysed in detail using the modular approach and the results can be used for LCA studies that are increasingly reliable and representative of real production processes. Bernardi et al. (2018a) integrated the analysis of technical aspects, such as the operational working time and work experience data, with economic and environmental assessments, focusing exclusively on olive harvesting operation.

The novelty of the proposed approach in this research makes it possible to develop sustainability studies to support stakeholder’s needs. In particular, the stakeholders as harvesting machine manufacturers will be able to evaluate the opportunity of investment in technologies with a lower environmental impact; the farmer can identify the critical elements of his activities and build a monitoring technique that allows the development of a system aimed at obtaining environmental certification and he will be able to improve his tools by optimizing technical efficiency and minimizing environmental impacts and costs. Furthermore, the applied methodology offers to the Public Authorities an additional tool to guide and evaluate the effects of environmental investment policies in the agricultural field, e.g. scenarios with reduced impacts can be defined and evaluated according to certain objectives of environmental sustainability.

2. Materials and methods

In order to achieve the above settled objectives, three different methods were utilised. Particulrly:

- technical analysis, focusing on work capacity and productivity referred to the operating working time, in each site was performed according to CIOSTA requirements - Commission Internationale de l'Organisation Scientifique du Travail en Agriculture (Bolli & Scotton, 1987), as carried out by Bernardi et al. (2018a).
- economic assessment was made by performing the "harvesting cost methodology" (Bernardi et al., 2016) using the method described by Miyata (1980). Among the different available methodologies such as full costing (Antonelli and D'Alessio, 2004), direct costing, activity based costing (Carli and Canavari, 2013) and life cycle costing (Stillitano et al., 2016), the one implemented in this study has been considered because it is precisely designed to accounts both of operating machinery cost and operator-machine labour cost.
- Life Cycle Assessment (ISO 14040:2006) was applied for environmental analysis. There are different methods related to environmental analysis, which have different purposes and are useful to analyse different facets of the environment. For example Environmental Impact Assessment - EIA is aimed at identifying, describing and assessing the environmental impacts of a project, the Ecological Footprint (Wackernagel and Rees, 1996) measures human demand on natural capital, Carbon Footprint of Product (ISO 14067:2018) and Water Footprint of Product (ISO 14046:2014) are aimed at identifying the carbon and water footprint of a process or a product respectively. In this context the LCA methodology represents the best methodological choice because it allows to evaluate the environmental impacts linked to a process or a product with a very wide perspective on the different areas of environmental protection, including human health, ecosystem and resources.

Initially, the work capacity and productivity in the different sites were evaluated. The processed data were used for subsequent economic and environmental assessments.The data were calculated with three alternative functional units (FUs): one hour of harvesting (1 h), one hectare of harvested area (1 ha), and one kilogramme of harvested product (1 kg).

2.1. Orchard features and harvesting scenario organisation

The experimental trials were conducted over three years on six autochthonous Calabrian cultivars, which are representative of the diverse productive contexts of the region. Harvesting sites I to IV enclosed *Olea europaea* L. ‘Ottobratica’ and ‘Grossa di Gerace‘ trees that were less than 50 years of age, whereas harvesting sites V to VIII were represented by traditional orchards that were over 100 years old with trees of *Olea europaea* L. ‘Sinopolese’, ‘Cassanese’, ‘Tondina’, and ‘Dolce di Rossano’ (Fig. 1). Tests were conducted in flat terrains under similar weather conditions, with trees in good physiological and health conditions whose dimensional and technical parameters are shown in Table 2. Harvesting site characteristics (employed machinery and number of workers), canopy volume calculated according to the International Olive Council (IOC, 2007) method, and the amount of olives per tree are shown in Table 3. The fruit removal force was equal to5.27 ± 2.70 N.

Table 2. *Average tree dimension parameters at the analysed harvesting sites (mean ± standard deviation)*

Harvesting site	Cultivar	Planting layout	Age	Trunk Ø	Crown insertion height	Canopy Ø	Plant height
		(m)	(year)	(cm)	(m)	(m)	(m)
I	Ottobratica	7×7	20	26.00 ± 3.41	1.10 ± 0.41	6.03 ± 0.18	4.18 ± 0.99
II	Ottobratica	9×9	50	52.65 ± 10.77	1.53 ± 0.10	7.90 ± 0.18	10.14±0.42
III	Grossa Gerace	6×4	20	26.84 ± 3.11	1.02 ± 0.24	4.86 ± 0.36	5.03 ± 0.55
IV	Grossa Gerace	6×4	20	28.16 ± 3.91	0.95 ± 0.25	4.79 ± 0.72	5.01 ± 0.44
V	Cassanese	10×10	>100	90.20 ± 34.6	1.60 ± 0.10	6.26 ± 0.15	5.59 ± 0.18
VI	Tondina	10×8	>100	37.10 ± 5.29	1.52 ± 0.59	5.64 ± 0.12	3.75 ± 0.14
VII	Dolce di Rossano	12×12	>100	67.40 ± 8.73	1.67 ± 0.45	6.78 ± 0.10	5.79 ± 0.66
VIII	Sinopolese	7×7	>100	59.45 ± 24.07	1.53 ± 0.83	6.21 ± 0.29	5.67 ± 0.19

Table 3. *Harvesting site composition and olive yield at harvest (mean ± SD)*

Harvestin	Employed machine/equipment	Worker	Canopy volume	Olive yield

g site				
			(m^3)	(kg/tree)
I	Self-propelled trunk shaker + nets	5	91.42 ± 33.39	40.05 ± 3.25
II	Self-propelled trunk shaker + nets	7	435.65 ± 174.39	84.15 ± 20.42
III	Manual + nets	3	75.07 ± 14.01	16.00 ± 2.23
IV	Mechanical pneumatic aids + nets	3	73.28 ± 9.91	13.52 ± 2.50
V	Self-propelled trunk shaker + nets	10	126.54 ± 48.21	54.00 ± 6.00
VI	Self-propelled trunk shaker + nets	10	55.85 ± 21.98	50.24 ± 8.00
VII	Self-propelled trunk shaker + nets	10	140.82 ± 25.22	54.50 ± 3.00
VIII	Self-propelled trunk shaker + nets	8	138.00 ± 79.17	65.30 ± 12.11

At six of the eight evaluated sites, harvesting was performed using a self-propelled trunk shaker with vibrating head from 600 kg (I, II, and VIII) to 450 kg (V, VI, and VII) with a multidirectional configuration of eccentric masses. One operator drove the harvesting machine while the others were in charge of the net and olive handling (Fig. 2). At site III, harvesting was entirely manual and at site IV, harvesting was performed using two mechanical pneumatic aids and nets (Fig. 3).

Figure 1. Olive trees at harvesting sites II (left) and VII (right)

Figure 2. Vibrating head and olive tree at site V

Figure 3. Olive harvesting at sites III (left) and IV (right)

2.2. Determination of work productivity and olive oil analysis

To determine the work productivity at the different harvesting sites, the times of each work phase were recorded, applying the classification proposed by the Commission Internationale de l’Organization Scientifique du Travail en Agriculture as described by Bolli and Scotton (1987), as reported above. Work productivity referred to the operative time was then calculated and expressed as the amount of harvested plants per hectare per worker. After the harvesting trials, a sample of olives from each scenario was collected and micro-milled for analysis according to CEE 2568/91 and EU 1348/2013 regulations. An experienced panel of eight judges performed the sensory analysis based on the IOC (2015) requirements.

2.3. *Statistical analysis*

One-way analysis of variance was applied to the data to determine significant differences between the result means. Duncan's multiple range test, with significance level $P < 0.05$ was considered. Free R software version 3.3.1 (R Foundation for Statistical Computing Platform) was used for data processing.

2.4. *Economic analysis*

Economic analysis was performed by evaluating the harvesting costs at each investigated site. The equations used for calculating these costs are shown in Table 4. First, the harvesting hourly cost (€ h^{-1}) was calculated considering the machine and net costs. The machine hourly cost was determined using the method described by Miyata (1980) based on the assumptions reported in the supplementary material. This type of analysis considers both the fixed and variable costs. The fixed costs consisted of the interest on capital goods and depreciation, insurance, and maintenance of the machinery and equipment. For the hourly variable costs, fuel and oil consumption and operator-machine labour cost were assessed. For the net costs, the fixed costs included depreciation and interest and the variable cost was related to the labour cost for the operators involved in the net handling.

Table 4. *Harvesting costs for each study site.*

Cost item	Unit	Formula
Harvesting cost per hour	€ h^{-1}	$Machine\,Hourly\,Cost\,(€\,h^{-1}) + Net\,Hourly\,Cost\,(€\,h^{-1})$
Harvesting cost per kg of olives	€ kg^{-1}	$\frac{Total\,Hourly\,Cost\,(€\,h^{-1})}{Harvesting\,Olive\,Yield\,per\,Hour\,(kg\,h^{-1})}$
Harvesting cost per kg of olive oil	€ kg^{-1}	$\frac{Total\,Hourly\,Cost\,(€\,h^{-1})}{Harvesting\,Olive\,Oil\,Yield\,per\,Hour\,(kg\,h^{-1})}$
Harvesting cost per hectare	€ ha^{-1}	$Harvesting\,Cost\,per\,kg\,of\,olives\,(€\,kg^{-1}) \times Harvesting\,\mathrm{Olive}\,Yield\,per\,ha\,(kg\,ha^{-1})$

The technical and economic data of the machinery were collected from direct measurements at the harvesting sites (Table 5). Further data were obtained from interviews with experts in the Calabrian olive sector. From these interviews, the practices that were widely performed at the farms were identified, and thus no theoretical assumptions were required (Paolotti et al., 2017). For the labour remuneration, the opportunity cost approach was adopted by assuming the employment of temporary workers for manual (net handling) and mechanical operations (Bernardi et al., 2016; Stillitano et al., 2016) and adopting the current hourly wage, which included social security contributions. The remuneration for the qualified workers undertaking mechanical operations was a gross pay of 8.60 € h^{-1}, whereas that for the other workers was equal to 7.20 € h^{-1}. Harvesting days were assumed to be 60 days per year at 8 h per day.

In addition, the following assumptions were made:

- The machine salvage value was estimated as the demolition material sale (steel and iron) that was equal to 10% of the initial purchase cost.
- For the nets, a purchase price of 500 € ha^{-1} and economic life of 5 years were used.
- The interest on capital goods (machines and nets) was calculated by applying an interest rate of 2%.

To evaluate the harvesting cost per kg of olives (€ kg^{-1}) for each study site, the total hourly cost was divided by the harvesting olive yield per hour. The harvesting cost per kg of olive oil (€ kg^{-1}) was calculated by dividing the total hourly cost by the harvesting olive oil yield per hour. The assumed olive oil yields used in the calculation were 10% for Ottobratica, 15% for Grossa di Gerace and Dolce di Rossano, and 18% for Cassanese, Tondina, and Sinopolese.

To compute the average cost per hectare, the harvest cost per kg of olives was multiplied by the harvested olive yield per hectare.

Table 5. *Technical features of the harvesting machines used at the different sites*

Site	I	II	IV	V	VI	VII	VIII
Machinery	Self-propelled trunk shaker	Self-propelled trunk shaker	Mechanical pneumatic aid	Self-propelled trunk shaker	Self-propelled trunk shaker	Self-propelled trunk shaker	Self-propelled trunk shaker
Purchase price (€)	58,000	60,000	2,000	65,000	65,000	70,000	60,000
Power (kW)	94.29	72.54	13.23	101.56	101.56	105.18	94.31
Economic life (years)	15	15	8	15	15	15	15
Average annual use (h year^{-1})	480	480	480	480	480	480	480
Fuel consumption (L h^{-1})	8.15	7.59	0.72	8.60	8.64	8.92	8.10
Oil consumption (L h^{-1})	0.20	0.20	0.02	0.21	0.21	0.21	0.20

2.5. Environmental analysis

The environmental analysis was performed using the LCA method. This method has gained great consensus in the scientific community as an effective solution for assessing the environmental burdens of a product or process. Two international standards (ISO 14040, 2006a; ISO 14044, 2006b) provide the framework and guidelines to perform a LCA.

First, the goal and scope of the study was defined. In the present study the objective was to assess the environmental performances of different olive harvesting systems.

Typically, agricultural processes are characterized by the multifunctionality that makes it necessary to use different Functional Units to analyze specific functions of the considered production system (Nemecek et al., 2015).

In this study, we will analyse only the unitary process of olive harvesting, whose function is the harvesting of the drupes, to provide results that can be used by other LCA practitioners as inventory data specific to the olive harvesting operation.

Considering that, for the different evaluated machines, the function "olive harvesting" can be measured per unit of worked hour per unit of harvested area or per harvested mass, three FUs were used: "1 h of harvesting operations" (Table 6), "1 ha of olive grove" (Table 7) and "1 kg of harvested olives" (Table 8), respectively.

The "1 h of harvesting operations" FU is a snapshot of different scenarios, which is independent of yield or work capacity. The results could be used within a "gate to gate" or "cradle-to-grave" framework of LCA studies on olive oil production. The "1 ha of olive grove" FU was used to evaluate the impacts of different harvesting practices in terms of area harvested, which is often implemented for the evaluation of impacts of orchard management, and the "1 kg of harvested olives" FU was used to evaluate the impacts related to the unit of the product, which is generally used for product assessment (Cerutti et al., 2015) and is mandatory for the product category rules to obtain table olives and olive oil certification.

To accomplish the objective of the present study for the assessment of environmental performances of different olive harvesting systems, the LCA was limited to the harvesting operation (Fig. 4). This choice, despite providing a partial analysis of life cycle impacts, was driven by the aim to create a modular LCA related to the olive harvesting operation, which would be useful as a tool for LCA practitioners and stakeholders in the olive oil sector. LCA can be adopted to create site-specific datasets that respond to the real technologies used during the production process. One of the main problems of an LCA study is related to the lack of specific data on production processes, which is especially true for agricultural production processes that are strongly influenced by the specificity of the production site.

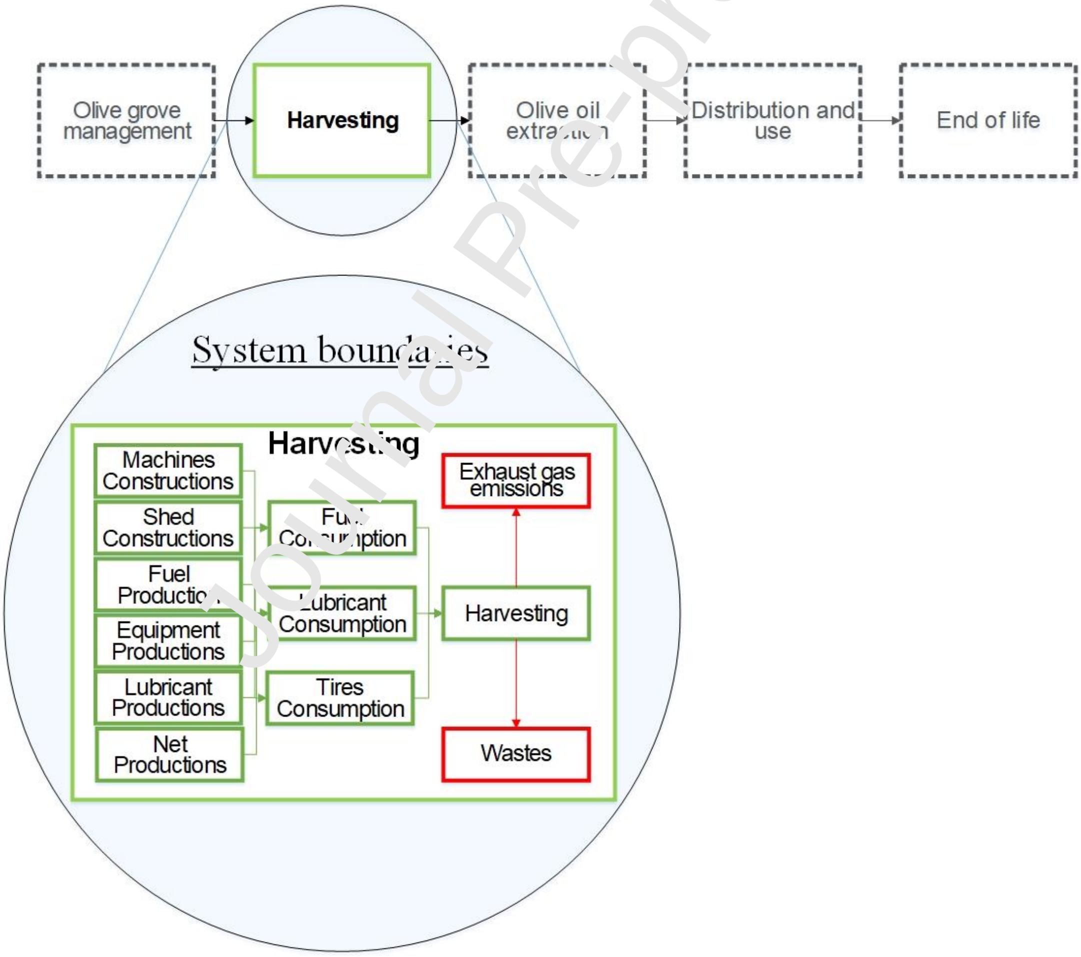


Figure 4. *System boundary flow chart*

According to Bernardi et al. (2018a), two different scaling methods should be used to adjust the inventory data to the two alternative FUs (equations can be found in the supplementary material).

The inventory data were directly collected during the harvesting operation at the different sites using a customised data collection form.

Inventory modelling followed Ecoinvent's principles for infrastructure and operations. Basic operation modules were designed for each scenario by detecting:

- Infrastructure, represented by agricultural machinery (eg. tractor or other powertrain), agricultural equipment (trunk shaker head or hand-held, pneumatic shaker) and shed
- Materials, represented by lubricant and nets
- Energy inputs, represented by diesel in all scenarios.

Emissions to air from combustion of the fuel and emissions to soil from tyre abrasion were estimated according to Nemecek and Kagi. (2007).

The consumption data (diesel and lubricant) were directly measured using the "tanks topping up" technique. The background data (diesel and lubricant production, machine production, maintenance and disposal) were retrieved from the Ecoinvent V. 3.4 database (Weidema et al., 2013).

Data quality analysis was carried out in accordance with Ecoinvent, using the pedigree matrix approach (see supplementary material).

Table 6. *Environmental life cycle impact - LCI (FU 1 h of olive harvesting)*

Site	Agricultural machinery kg h^{-1}	Agricultural equipment kg h^{-1}	Diesel l h^{-1}	Shed m^2 h^{-1}	Lubricant kg h^{-1}	Net m^2 h^{-1}
I	8.75E-01	8.33E-02	8.15E+00	1.53E-03	2.88E-02	8.63E+00
II	6.74E-01	8.33E-02	7.59E+00	1.53E-03	6.52E-02	1.96E+01
III	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	5.32E-01
IV	2.04E-01	1.42E-02	7.20E-01	1.53E-03	2.95E-04	8.86E-01
V	7.36E-01	6.25E-02	8.60E+00	1.53E-03	6.92E-02	1.98E+01
VI	7.36E-01	6.25E-02	8.64E+00	1.53E-03	6.39E-02	1.82E+01
VII	8.26E-01	6.25E-02	8.92E+00	1.67E-03	1.04E-01	2.96E+01
VIII	7.36E-01	8.33E-02	8.10E+00	1.53E-03	2.01E-02	6.04E+00

Table 7. *Environmental life cycle impact - LCI (FU 1 ha)*

Site	Agricultural machinery	Agricultural equipment	Diesel	Shed	Lubricant	Net
	kg ha^{-1}	kg ha^{-1}	l ha^{-1}	m^2 ha^{-1}	kg ha^{-1}	m^2 ha^{-1}
I	6.08	0.58	56.68	0.01	0.20	60.00
II	2.07	0.26	23.28	0.00	0.20	60.00
III						60.00
IV	13.82	0.96	48.72	0.10	0.02	60.00
V	2.23	0.19	26.10	0.00	0.21	60.00
VI	2.42	0.21	28.41	0.01	0.21	60.00
VII	1.67	0.13	18.05	0.00	0.21	60.00
VIII	7.31	0.83	80.42	0.02	0.20	60.00

Table 8. *Environmental life cycle impact - LCI (FU 1 kg of harvested olives)*

Site	Agricultural machinery	Agricultural equipment	Diesel	Shed	Lubricant	Net
	kg kg^{-1}	kg kg^{-1}	l kg^{-1}	m^2 kg^{-1}	kg kg^{-1}	m^2 kg^{-1}
I	7.44E-04	7.09E-05	6.93E-03	1.30E-06	2.45E-05	7.34E-03
II	1.99E-04	2.46E-05	2.24E-03	4.51E-07	1.93E-05	5.78E-03
III	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	9.00E-03
IV	2.45E-03	1.70E-04	8.65E-03	1.84E-05	3.55E-06	1.07E-02
V	4.14E-04	3.51E-05	4.83E-03	8.59E-07	3.89E-05	1.11E-02
VI	3.85E-04	3.27E-05	4.52E-03	8.00E-07	3.34E-05	9.55E-03
VII	4.42E-04	3.34E-05	4.77E-03	8.91E-07	5.55E-05	1.59E-02
VIII	5.48E-04	6.21E-05	6.03E-03	1.14E-06	1.50E-05	4.50E-03

For the machinery (main machinery used in harvesting operations), shed, equipment (equipment used in combination with the machinery), and net production allocation was carried out considering their use in the harvesting operation and their useful life.

It was decided to limit maintenance to the only use of lubricating oil, adopting as an exclusion criterion, the omission of grease and other materials of minor importance (eg. water, liquids for pneumatic systems) from the inventory. This would have a negligible incidence on the results (less than 1%).

In the life cycle impact assessment (LCIA) phase, the environmental impact data were processed using SimaPro 8.5 software (Goedkoop et al., 2013b) and the ReCiPe method (2008 version) at the midpoint and endpoint levels (Goedkoop et al., 2013a) was chosen to process the results from each analysed site. The results of the characterisation using the midpoint method was only used for the primary FU (1 h of harvesting operation) to evaluate the impacts of different technical solutions from the point of view of the potential environmental effects. These impacts were also represented using the endpoint method and compared with the supplementary FUs to underline the variations due to different FUs based on the environmental damages caused, although the uncertainty of the results increases using this method (Goedkoop et al., 2013a). The choice to use the 2008 version of the ReCiPe method rather than the 2016 version was due to the latter lacking normalisation and weighting factors for the endpoint perspective. Thus, to ensure that the obtained results were complementary and comparable with those of the Bernardi et al. (2018a) study, the same LCIA methods were used.

Moreover, following the results examination, a sensitivity analysis was carried out in order to assess the effects, in terms of environmental impacts, generated by the variation of the main hotspots that emerged in this study.

3. Results and discussions

3.1 Work productivity assessment

The calculated work capacity and productivity referred to the operating time, as well as the harvesting efficiency consisting in the ratio between the quantity of mechanically harvested olives and the total mass on the tree, are shown in Table 9.

Table 9. *Work capacity, work productivity, and harvesting efficiency at the study sites*

Site	Work capacity	Work productivity	Harvesting efficiency
	kg h^{-1}	kg h^{-1}worker^{-1}	%
I	1175.32	232.14	70
II	3386.61	484.81	78
III	59.12	19.82	96
IV	83.21	27.81	90
V	1779.12	177.90	92
VI	1910.13	197.21	93
VII	1870.12	187.33	92
VIII	1342.33	168.12	89

The different responses for the production and efficiency of the harvesting systems reflect the heterogeneity of the study sites. At site I, at least 8 h was needed to collect the entire production from 1 ha, equal to approximately 8 tonnes. These values significantly improve at site II, characterised by plants of the Ottobratica cultivar, where the work capacity required only 3.5 hours ha^{-1} for a production of 12 tonnes. Thus, excellent results can be achieved in young olive orchards, which include plants that are designed to encourage the implementation of mechanical harvesting, even for cultivars that are characterised by scalar production that lower the harvesting efficiency. In these cases, at least two harvesting phases are necessary, at different times, to maximise the quantity of drupes collected.

When assessing the orchards containing trees over 100 years old, the number of workers required to manage the harvesting site increased to obtain an average production of 55 ± 7 kg/orchard. At harvesting sites V and VI, the entire production of 1 ha (average 5.5 tonnes) was harvested in approximately 4 h. However, for site VII, it took less than 3 h on average for the harvesting of the entire production of 1 ha (approximately 4 tonnes). At site VIII, despite eight workers, more than one day was required to collect the entire production of 1 ha, equal to approximately 13 tonnes.

The results obtained were influenced by the characteristics of the olive tree, the pedoclimatic features, variety, and harvesting time, as well as the mechanical means employed and the organisation of the harvesting site. Bernardi et al (2018a) noted that it was possible to harvest up to 500 kg h^{-1} $worker^{-1}$ in young olive groves of Carolea, whereas Famiani et al. (2014) calculated a working productivity of over 100 kg h^{-1} $worker^{-1}$ for centenarian plants in Cellina di Nardò.

At sites III and IV, manual and mechanical aids were used, respectively. Compared to that obtained using the mechanised systems, the working time was much higher; therefore, to collect 7 tonnes of product in 1 ha, up to 15 working days were required. This result was significantly improved using pneumatic aids, which almost halved the working time and had a high harvesting efficiency (90%). Sola-Guirado et al. (2014) achieved a harvesting efficiency value of 98% for Hojiblanca cultivars using pneumatic aids, whereas in the study by Bernardi et al. (2018a), this value was 81% using a hand engine shaker. Amirante, Tamborrino, and Leone (2012) calculated a harvesting efficiency of 70% for Leccino cultivars using a hand engine shaker and 93% using hand pneumatic combs with nets.

The chemical characteristics of the olive oil obtained from the studied orchards are shown in Table 10. Free acidity expressed as the percentage of oleic acid, peroxide value, and the UV absorbencies at 232, 266, 270, and 274 nm were calculated (Giuffrè, 2014). All the studied olive oil fit within the limits established by the IOC for the extra virgin olive oil category. The sensorial analysis confirmed that these oils belonged to the category of extra virgin, with the median of the defect = 0 and the median of the fruitiness > 0.

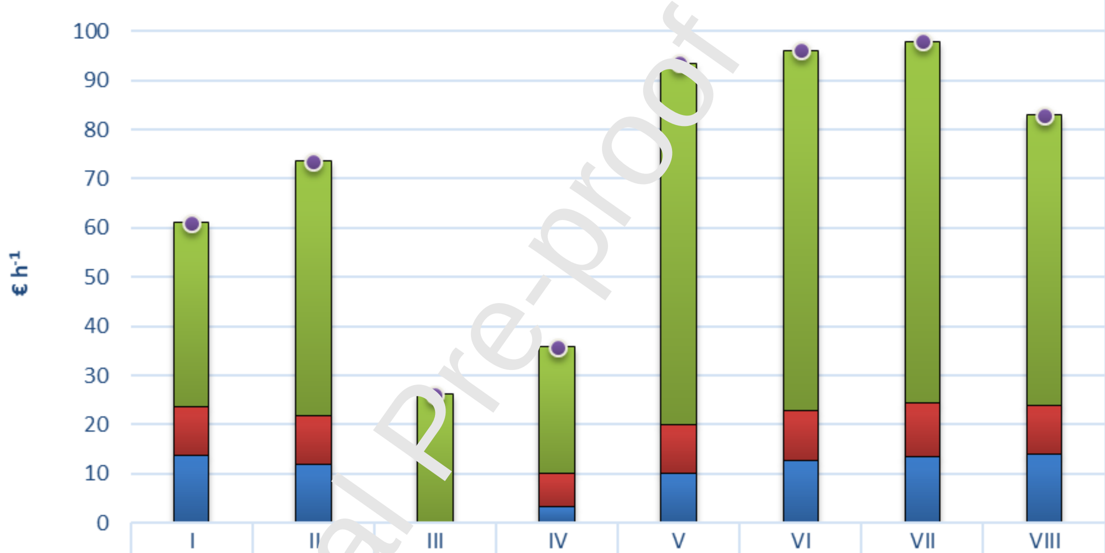
Table 10. *Chemical characteristics of the analysed oils*

	I	II	III	IV	V	VI	VII	VIII	Sig.	Reg. UE 1830/2015
Acidity % acid oleic	0.31^{c}	0.15^{a}	0.42^{d}	0.72^{e}	0.36^{c}	0.25^{b}	0.47^{d}	0.35^{cd}	**	≤0.8
Peroxide value (meq O_2 kg^{-1})	8.29^{c}	5.70^{b}	8.85^{c}	4.85^{a}	6.67^{bc}	7.46^{c}	5.05^{b}	17.30^{d}	**	≤20
K232	1.86	1.82	1.90	1.70	1.83	2.04	1.81	1.75	n.s.	≤2.50
K266	0.11	0.14	0.14	0.09	0.15	0.15	0.13	0.14	n.s.	-
K270	0.11	0.12	0.12	0.08	0.13	0.15	0.12	0.13	n.s.	≤0.22
K274	0.09	0.14	0.11	0.08	0.11	0.13	0.09	0.13	n.s.	-
Delta K	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	n.s.	≤0.01

3.2 Economic assessment

The economic results of the harvesting systems varied significantly depending on the mechanisation level at each site. The results of the harvesting hourly costs are summarised in Figure 5. A higher cost per hour (97.90 € h^{-1}) was calculated for site VII, followed by sites VI (96.16 € h^{-1}) and V (93.45 € h^{-1}). The highest contributors to the cost were the variable costs, which ranged from 89% for site V to 86% for sites VI and VII. Labour and fuel consumption costs were the main costs of the variable costs. The highest fixed costs were found for sites VIII and I (23% and 17% of the total hourly cost, respectively). This was largely due to the depreciation and maintenance costs of the machinery. The lowest hourly costs were found for sites III (26.09 € h^{-1}) and IV (31.52 € h^{-1}), where manual and hand-held harvesting were performed. At both sites, the labour cost was the largest contributor to the total cost contributing between 72% and 99%. There was a higher use of labour in the traditional orchards (sites I, II, V, VI, VII, and VIII) than that in the intensive ones (sites III and IV) because of the higher number of operators required to use the nets and handle the olives.

Table 11 includes a summary of the harvesting unit costs at each study site. Similar to a previous study (Bernardi et al., 2018a), these results were directly related to the different harvesting techniques regarding the employed machine/equipment and labourer number and the obtained yields estimated as a function of the operative time and plant productivity at all sites. Therefore, the mechanical harvesting systems (sites I, II, V, VI, VII, and VII) had better economic performance than those of the hand-held harvesting systems (sites III and IV).



	I	II	III	IV	V	VI	VII	VIII
🟩 Labour cost	37.40	51.80	25.80	25.80	73.40	73.40	73.40	59.00
🟥 Variable machinery costs	10.00	10.00	-	6.72	10.10	10.10	11.10	10.00
🟦 Hourly fixed costs	13.71	11.81	0.29	3.28	9.95	12.66	13.40	13.89
● Total hourly cost	61.11	73.61	26.09	35.80	93.45	96.16	97.90	82.89

Figure 5. Economic assessment results: hourly costs of harvesting

For the cost per kg of harvested olives, the lowest cost (0.022 € kg^{-1}) was found at harvesting site II, whereas the highest value was obtained at site III (0.44 € kg^{-1}), considering the hourly harvested yields of 3386.61 and 59.12 kg h^{-1}, respectively. For both systems, the variable costs represented the highest contributor to the total cost, which were equal to 83.9% for the former and 98.9% for the latter. Similar costs per kg of olives (0.052 € kg^{-1}) were achieved at sites I and VII, where high work capacities (1,175.32 and 1,870.12 kg h^{-1}, respectively) were observed. Regarding the cost per kg of olive oil, sites III (manual harvesting) and IV (hand-held harvesting) had the worst economic performance, reaching an estimated value of 2.94 and 2.53

€ kg^{-1}, respectively. The sites that used mechanical harvesting systems had the best performance, with an obvious cost reduction, which was in agreeance with the results obtained by Sperandio et al. (2017).

Similar to the results obtained by Famiani et al. (2014), the unitary cost to harvest 1 kg of olives and 1 kg of olive oil was affected by the hourly machine cost and working productivity of the harvest system and the oil content of the olives.

Table 11. *Economic assessment results: harvesting unit costs*

Cost item	Site							
	I	II	III	IV	V	VI	VII	VIII
Harvesting cost per kg of olives (€ kg^{-1})	0.052	0.022	0.44	0.38	0.053	0.050	0.052	0.062
Harvesting cost per kg of olive oil (€ kg^{-1})	0.52	0.22	2.94	2.53	0.29	0.28	0.35	0.34
Harvesting cost per hectare (€ ha^{-1})	415.97	260.83	3,089.54	2,134.14	288.88	276.87	209.41	802.81

Regarding the average cost per hectare, the sites that used manual and hand-held harvesting systems (III and IV) showed higher costs than those sites that used mechanical systems, estimated at 3,089.54 and 2,134.14 € ha^{-1}, respectively. This was mainly due to the higher time dedicated to harvesting, which was approximately 15 working days for manual harvesting and eight working days for hand-held systems. Thus, mechanical harvesting is the only way to decrease production costs and increase the sustainability of the production of olives, confirming the results of studies by Fernandez Escobar et al. (2013) and Ravetti (2014). Other studies (Freixa et al., 2011; Stillitano et al., 2017; Vieri & Sarri, 2010) are consistent with the findings obtained in the present study, confirming that the economic sustainability of olive cultivation can be improved by the use of mechanical harvesting solutions.

In addition, the research results showed positive effects of the use of mechanical harvesting on the management of traditional olive orchards, substantially improving the olive oil quality compared to that obtained from harvesting from the ground, endorsing the results obtained by Almeida and Peça, (2012), Bernardi et al. (2016), and Sola-Guirado et al. (2014).

3.3 Environmental assessment

The analysis of environmental impacts was first performed by analysing the ecoprofile at the midpoint level at the different harvesting sites. The results obtained from the implementation of the modular LCA method showed that site III used the best solution from an environmental point of view (Table 12). However, this result was expected as site III was the only site that was exclusively manual. Human work is not accounted for in the characterisation factors of the ReCiPe method; therefore, the impacts were linked only to the use of nets. Although this type of harvesting is still widely practiced, especially for niche production systems, the higher quality olive oil sector is moving towards mechanised harvesting techniques that combine good product quality with lower harvesting costs. Similar consideration could be made at site IV, where the harvesting was mechanically aided, but was still dependent on human labour.

Table 12. *Life cycle impact assessment (LCIA) results at the midpoint level (FU 1 h of olive harvesting)*

Impact category	Unit	I	II	III	IV	V	VI	VII	VIII
Climate change	kg CO2 eq	3.61E+01	4.02E+01	3.41E-01	4.31E+00	4.37E+01	4.28E+01	5.15E+01	3.35E+01
Ozone depletion	kg CFC-11 eq	5.20E-06	4.81E-06	4.49E-09	6.06E-07	5.39E-06	5.40E-06	5.72E-06	5.02E-06
Terrestrial acidification	kg SO2 eq	2.51E-01	2.84E-01	2.47E-03	2.75E-02	3.09E-01	3.03E-01	3.65E-01	2.34E-01
Freshwater eutrophication	kg P eq	5.25E-03	6.05E-03	7.81E-05	1.11E-03	6.32E-03	6.10E-03	8.14E-03	4.33E-03
Marine eutrophication	kg N eq	1.36E-02	1.36E-02	5.26E-05	1.46E-03	1.51E-02	1.50E-02	1.67E-02	1.31E-02
Human toxicity	kg 1,4-DB eq	8.06E+00	8.41E+00	8.25E-02	1.80E+00	8.88E+00	8.64E+00	1.10E+01	6.76E+00
Photochemical oxidant formation	kg NMVOC	3.66E-01	3.63E-01	1.24E-03	3.84E-02	4.04E-01	4.02E-01	4.42E-01	3.53E-01
Particulate matter formation	kg PM10 eq	1.33E-01	1.38E-01	7.48E-04	1.45E-02	1.52E-01	1.51E-01	1.72E-01	1.27E-01
Terrestrial ecotoxicity	kg 1,4-DB eq	2.07E-03	2.01E-03	1.07E-05	3.68E-04	2.17E-03	2.14E-03	2.51E-03	1.85E-03
Freshwater ecotoxicity	kg 1,4-DB eq	1.94E-01	2.02E-01	1.90E-03	4.34E-02	2.12E-01	2.07E-01	2.63E-01	1.64E-01
Marine ecotoxicity	kg 1,4-DB eq	1.94E-01	1.98E-01	1.77E-03	4.34E-02	2.09E-01	2.04E-01	2.57E-01	1.64E-01
Ionising radiation	kBq U235 eq	3.28E+00	3.52E+00	2.98E-02	4.94E-01	3.79E+00	3.71E+00	4.52E+00	2.94E+00
Agricultural land occupation	m2a	1.66E+00	1.79E+00	1.17E-02	1.08E+00	1.82E+00	1.79E+00	2.17E+00	1.52E+00

Urban land occupation	m2a	3.31E-01	3.68E-01	2.45E-03	2.21E-01	3.76E-01	3.69E-01	4.46E-01	3.11E-01
Natural land transformation	m2	1.03E-02	9.89E-03	2.03E-05	1.24E-03	1.10E-02	1.10E-02	1.19E-02	1.00E-02
Water depletion	m3	2.57E-01	4.41E-01	9.73E-03	3.66E-02	4.53E-01	4.25E-01	6.41E-01	2.00E-01
Metal depletion	kg Fe eq	2.63E+00	2.27E+00	6.92E-03	6.23E-01	2.39E+00	2.37E+00	2.75E+00	2.25E+00
Fossil depletion	kg oil eq	1.14E+01	1.27E+01	1.05E-01	1.34E+00	1.38E+01	1.35E+01	1.63E+01	1.06E+01

If we consider the remaining six sites, the performances were comparable; however, the results from site VII showed the most influential solution and site VIII had the least. From a technological point of view, the six sites were comparable because they adopted the same collection system but used tractors with different powers and vibrating heads of different masses.

Pattara et al. (2016) have obtained a carbon footprint related to harvesting operations that varies between 0.147 kg CO_2 eq/5 l EVOO and 0.59 kg CO_2 eq/5 l EVOO. Considering an oil yield of about 15% for our scenarios and scaling the results according to the FU chosen by Pattara et al. (2016) the range of carbon emissions generated from the studied scenarios vary from 0.19 kg CO_2 eq/5 l EVOO to 1.70 kg CO_2 eq/5 l EVOO. Considering that Pattara et al. (2016) only took into account “Electricity production, transport and loss” and “Amount of diesel” used during harvesting, we can consider our results comparable to theirs. The collected data and the obtained results allow practitioners, who require accurate data for their analysis, to use the most appropriate scenario for their needs.

The inventory data were also processed at the endpoint level by calculating the single score impact of different scenarios. This allowed an easy comparison of the environmental performances of the analysed harvesting systems for both the main and alternative FUs.

The endpoint method was used to determine the contribution of different inputs and outputs on the total influence of the different sites. Figure 6 represents the contribution analysis and highlights the influence that diesel production and combustion had on the environmental profile and mechanically-aided olive harvesting.

Tsarouhas et al. (2015) reported a diesel consumption for the harvesting operation equal to 20.4l of diesel/acre. When considering the conversion to consumption per hectare we obtain a consumption value similar to that found for scenario I (55.08 l/acre) where diesel impact was in the order 66% of total impacts. The impacts related to the cultivation phase are reported in aggregated form so it is not possible to make a direct comparison of the results, however they also report only the fuel consumption in the inventory items.

In relation to the impacts due to diesel consumption, it should be noted that Fantozzi et al. (2015) found a reduction of about 100 kg CO_2 eq/ha hectare using, in the scenarios they analysed, electric rakes.

The second contributor to the impacts was represented by the nets and the third by the tractor. These three elements represented 95% of the total impacts on olive harvesting. Site III was influenced solely by net production, which was the only tool used during manual harvesting at this site. This distribution was also reflected in terms of the impact categories. From the analysis of site I, the contribution of single input and output showed that diesel production and combustion impacted on average 66% in terms of human health, ecosystems, and resources. A total of 13% was contributed by the nets and 16% from the tractor.

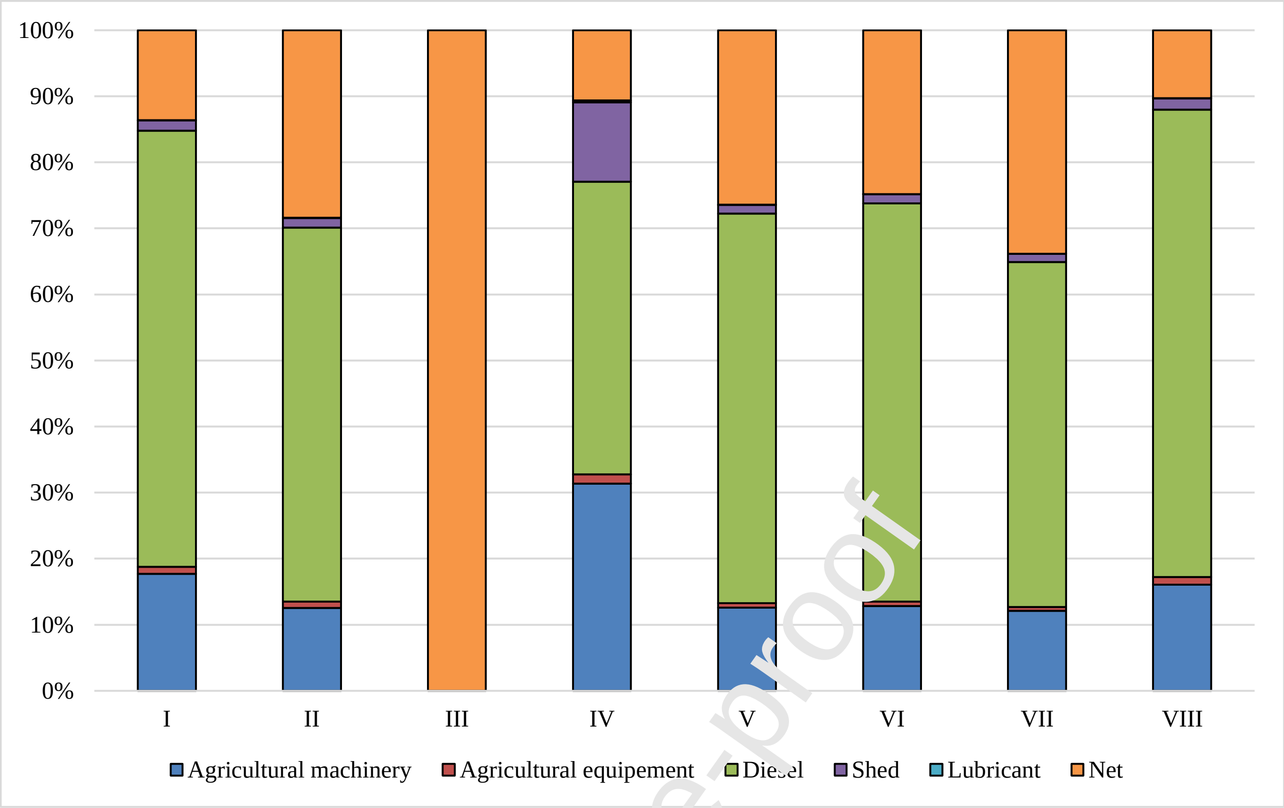


Figure 6. *Incidence of environmental impacts per LCI category at the endpoint level FU 1 h of olive harvesting*

Sites II, V, VI, and VII showed an overlapping ecoprofile, as did sites I and VIII, where diesel had more incidence owing to higher consumption during harvesting operations. Site IV had a higher impact on the production of agricultural machinery; however, this type of impact distribution was attributable to the lower consumption of diesel by the pneumatic compressor compared to the tractor.

Figure 7 shows the results reported in Table 3.4 for the endpoint level by aggregating the impacts per protection area. According to Bernardi et al. (2018a), the endpoint level leads to an uncertain increase in results; however, the single score representation is a quick way to show the performance of different “modules”. Comparing the variance between different sites at both the midpoint and endpoint levels showed that the results were comparable.

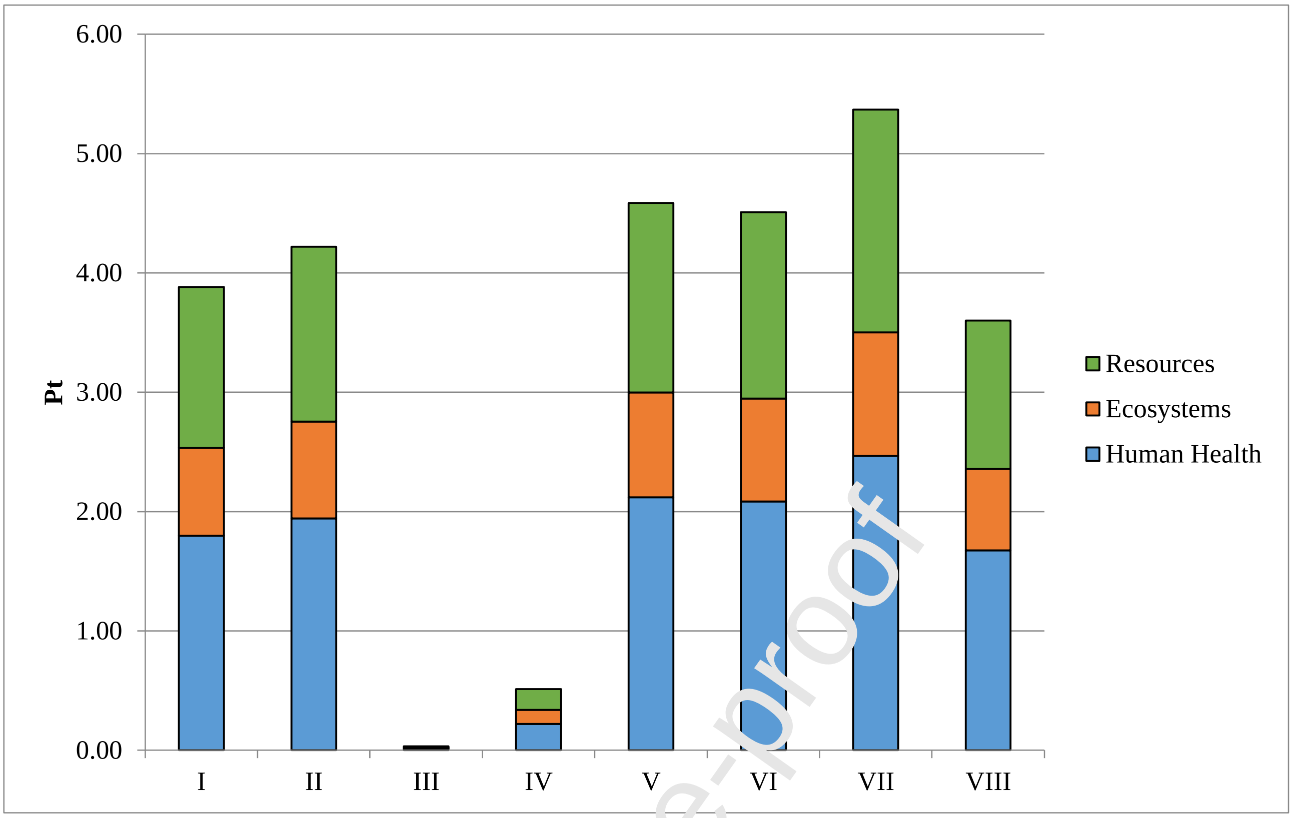


Figure 7. *LCIA results at the endpoint level (FU 1 h of olive harvesting).*

LCIA was also performed using two alternative FUs: "1 ha of olive grove" (Fig. 8) and "1 kg of harvested olives" (Fig. 9). These alternatives were included to create a more sensitive analysis and test the effectiveness of the modular approach operationally.

Results in terms of the area harvested were strictly dependent on the yield and working capacity of the different harvesting systems. Therefore, sites I and VIII were the most impacted because of their higher yields and lower working capacities. Sites II, V, VI, and VII were characterised by higher working capacities and lower yields; therefore, impacts per hectare were low. Sites III and IV had lower yields but also the lowest working capacities; therefore, especially at site IV, impacts per hectare were comparable with the mechanical harvesting systems.

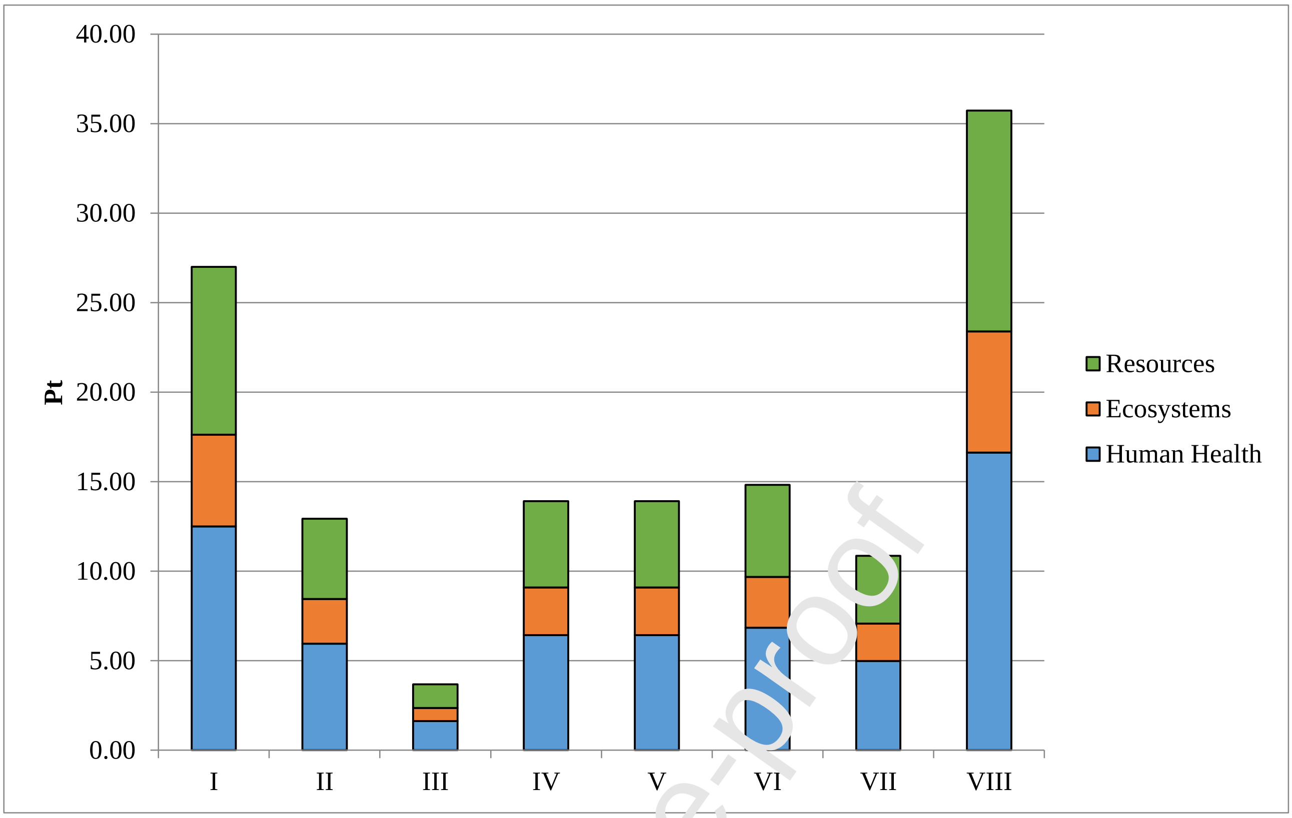


Figure 8. *LCIA results at the endpoint level (FU 1 ha of harvested area)*

Results in terms of mass harvested were only influenced by the working capacity and were the most representative for the LCA of olives and olive oil production, being performed in function of “mass-based FU”. The analysis of findings showed that in this case mechanical harvesting usually had the same performance except for sites II and I that obtained the best and worst results of the mechanised systems, respectively. The harvesting systems at sites I and II were tested on the same cultivar; however, the yield per hectare was different and the working capacity at site II was influenced by yield per hectare. Site IV had the worst performance because of a weak working capacity whereas site III, which was also characterised by a weak working capacity, obtained the best performance because it had the lowest impacts per hour.

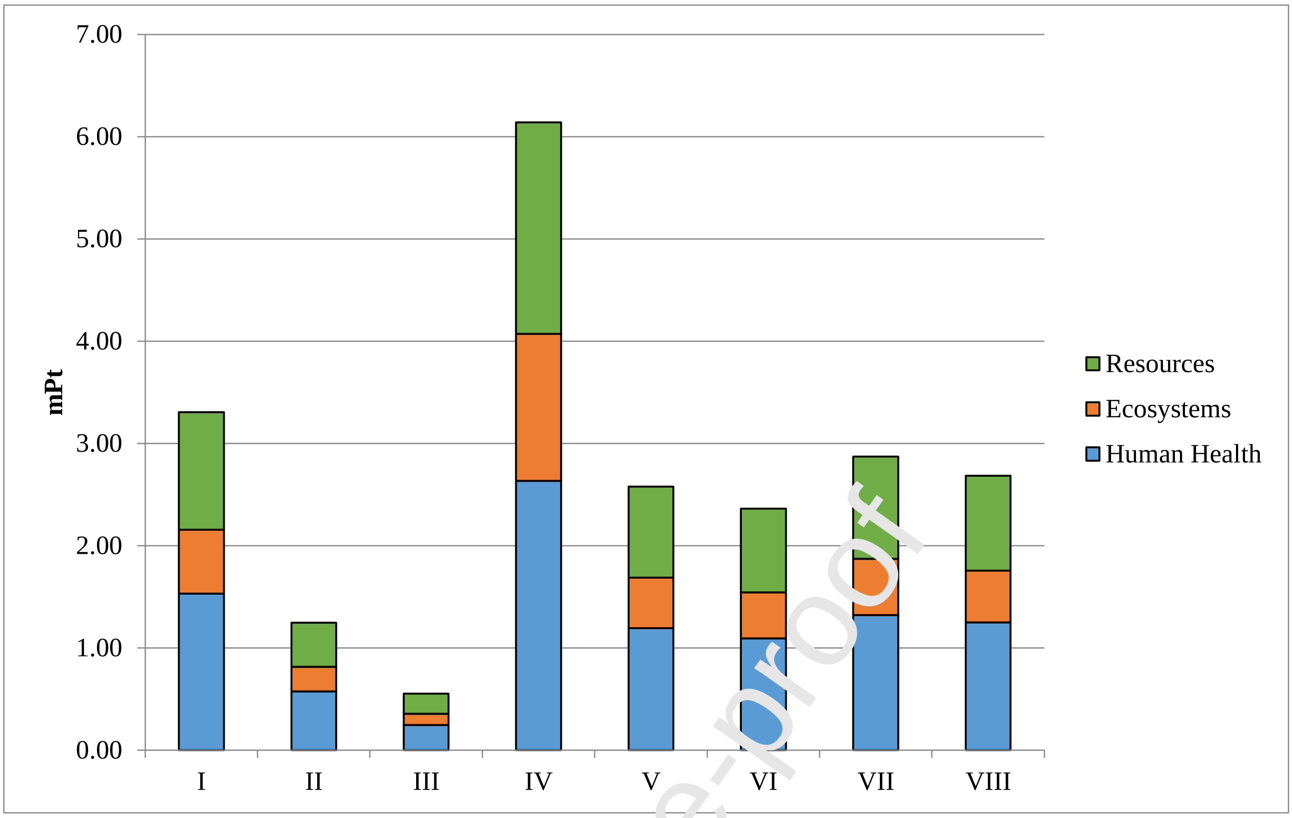


Figure 9. *LCIA results at the endpoint level (FU 1 kg of harvested olives).*

The results were in accordance with those of Bernardi et al. (2018a), underlining how the use of FUs linked to area harvested or working capacity are closely related to the results of the technical trials and, therefore, cannot be generalised to define a performance ranking.

Climate change represented the most representative impact category. The LCIA method splits this category into two areas of protection, human health and ecosystem, and the sum of the impacts represented 42% in all scenarios and for all FUs used. Pergola et al. (2013) and Mohamad et al. (2014) attributed the most influential operation in the olive orchard to be the harvesting operation. Fossil fuel depletion and particulate matter formation represent categories that are highly influenced by the harvesting operation and, as we can see by comparing the results from the present study with those of Bernardi et al. (2018a), these three impact categories were influenced by diesel production and combustion, which represent the major environmental hotspots.

On the basis of the results discussed so far, it was decided to carry out a sensitivity analysis by replacing the use of nets, which represent the second most impacting hotspot, with a specific tool for collection called "wrap-around catching frame". This tool consists of an inverted umbrella that wraps around the trunk of the plant, allowing a faster execution of the drupe collection. In the basic version it consists of a metal structure weighing about 150 kg on which a circular net with a diameter of 7 meters is permanently mounted.

Based on the results of Famiani et al. (2014), this instrument would allow an increase in the hourly harvesting yield of about 30%.

We, as a precautionary measure, have assumed that the use of the wrap-around catching frame allows a 5% reduction in collection times on average. Therefore, the environmental impacts were estimated according to the three FUs used in the study.

As it can be seen from Table 13, which shows the modified inventory for sensitivity analyses, the replacement of nets with the inverted umbrella affected only the reduction of the used net area but caused the increase in the weight of Agricultural Equipment employed.

Nevertheless, it is possible to observe a general reduction in the environmental impacts associated to olive harvesting, as it can be seen by analysing the relationship between the results presented in Table 14 and those related to the baseline scenarios presented in Table 12 (Sensitive/Baseline).

Table 13 - Environmental Life Cycle Inventory for sensitivity analysis (FU 1h of olives harvesting)

Scenario	Agricultural Machinery	Agricultural Equipment	Diesel	Shed	Lubricant	Net
	kg h^{-1}	kg h^{-1}	l h^{-1}	m^2 h^{-1}	kg h^{-1}	m^2 h^{-1}
I	8.75E-01	1.04E-01	8.15E+00	1.53E-03	3.03E-02	5.83E+00
II	6.74E-01	1.04E-01	7.59E+00	1.53E-03	6.86E-02	1.32E+01
III	0.00E+00	2.08E-02	0.00E+00	0.00E+00	0.00E+00	3.59E-01
IV	2.04E-01	3.50E-02	7.20E-01	1.53E-03	3.11E-04	5.99E-01
V	7.36E-01	8.33E-02	8.60E+00	1.53E-03	7.28E-02	1.34E+01
VI	7.36E-01	8.33E-02	8.64E+00	1.53E-03	6.72E-02	1.23E+01
VII	8.26E-01	8.33E-02	8.92E+00	1.67E-03	1.09E-01	2.00E+01
VIII	7.36E-01	1.04E-01	8.10E+00	1.53E-03	2.12E-02	4.08E+00

Table 14 – Environmental impacts of sensitivity scenarios

Impact category	Unit	I	II	III	IV	V	VI	VII	VIII
Climate change	kg CO2 eq	3.44E+01	3.62E+01	3.55E-01	4.21E+00	3.97E+01	3.91E+01	4.55E+01	3.23E+01
	Sensitivity/Baseline	-4.75%	-9.90%	4.08%	-2.26%	-9.21%	-8.66%	-11.79%	-3.50%
Ozone depletion	kg CFC-11 eq	5.18E-06	4.76E-06	9.08E-09	6.12E-07	5.34E-06	5.35E-06	5.65E-06	5.01E-06
	Sensitivity/Baseline	-0.32%	-0.93%	101.98%	0.96%	-0.84%	-0.77%	-1.27%	-0.17%
Terrestrial acidification	kg SO2 eq	2.39E-01	2.55E-01	2.16E-03	2.65E-02	2.80E-01	2.76E-01	3.20E-01	2.26E-01
	Sensitivity/Baseline	-5.06%	-10.26%	-12.40%	-3.71%	-9.52%	-8.96%	-12.14%	-3.75%
Freshwater eutrophication	kg P eq	4.88E-03	5.16E-03	1.10E-04	1.11E-03	5.41E-03	5.27E-03	6.77E-03	4.08E-03
	Sensitivity/Baseline	-7.07%	-14.75%	40.32%	-0.20%	-14.28%	-13.61%	-16.86%	-5.73%
Marine eutrophication	kg N eq	1.33E-02	1.30E-02	5.70E-05	1.45E-03	1.45E-02	1.44E-02	1.57E-02	1.29E-02
	Sensitivity/Baseline	-1.94%	-4.48%	8.37%	-0.84%	-4.08%	-3.79%	-5.60%	-1.36%
Human toxicity	kg 1,4-DB eq	7.68E+00	7.47E+00	1.15E-01	1.80E+00	7.93E+00	7.77E+00	9.59E+00	6.50E+00
	Sensitivity/Baseline	-4.80%	-11.14%	39.12%	0.12%	-10.68%	-10.08%	-13.09%	-3.81%
Photochemical oxidant formation	kg NMVOC	3.60E-01	3.49E-01	1.43E-03	3.82E-02	3.89E-01	3.88E-01	4.20E-01	3.49E-01
	Sensitivity/Baseline	-1.68%	-3.94%	15.68%	-0.55%	-3.57%	-3.32%	-4.96%	-1.16%
Particulate matter formation	kg PM10 eq	1.29E-01	1.29E-01	8.47E-04	1.43E-02	1.43E-01	1.43E-01	1.58E-01	1.24E-01
	Sensitivity/Baseline	-2.80%	-6.27%	13.26%	-1.07%	-5.75%	-5.36%	-7.73%	-1.98%
Terrestrial ecotoxicity	kg 1,4-DB eq	2.02E-03	1.89E-03	1.88E-05	3.74E-04	2.05E-03	2.04E-03	2.32E-03	1.83E-03
	Sensitivity/Baseline	-2.16%	-5.78%	74.83%	1.67%	-5.40%	-5.01%	-7.26%	-1.49%
Freshwater ecotoxicity	kg 1,4-DB eq	1.86E-01	1.81E-01	3.29E-03	4.41E-02	1.91E-01	1.88E-01	2.30E-01	1.59E-01
	Sensitivity/Baseline	-4.27%	-10.40%	73.11%	1.58%	-9.99%	-9.40%	-12.44%	-3.23%
Marine ecotoxicity	kg 1,4-DB eq	1.86E-01	1.75E-01	3.19E-03	4.42E-02	1.89E-01	1.86E-01	2.27E-01	1.59E-01
	Sensitivity/Baseline	-3.92%	-9.77%	80.27%	1.75%	-9.38%	-8.80%	-11.78%	-2.93%
Ionising radiation	kBq U235 eq	3.14E+00	3.18E+00	2.70E-02	4.95E-01	3.45E+00	3.40E+00	4.00E+00	2.85E+00
	Sensitivity/Baseline	-4.27%	-9.60%	-9.26%	0.19%	-9.02%	-8.47%	-11.52%	-3.15%
Agricultural land occupation	m2a	1.60E+00	1.65E+00	1.20E-02	1.08E+00	1.69E+00	1.66E+00	1.97E+00	1.49E+00
	Sensitivity/Baseline	-3.38%	-7.50%	2.57%	-0.08%	-7.43%	-6.97%	-9.47%	-2.47%
Urban land occupation	m2a	3.39E-01	3.39E-01	2.82E-03	2.20E-01	3.47E-01	3.43E-01	4.03E-01	3.03E-01
	Sensitivity/Baseline	-3.63%	-7.71%	14.96%	-0.20%	-7.63%	-7.15%	-9.73%	-2.62%
Natural land transformation	m2	1.03E-02	9.66E-03	2.74E-05	1.24E-03	1.08E-02	1.08E-02	1.15E-02	9.94E-03
	Sensitivity/Baseline	-0.93%	-2.30%	35.06%	0.17%	-2.08%	-1.93%	-2.96%	-0.62%
Water depletion	m3	2.06E-01	3.26E-01	7.24E-03	3.22E-02	3.36E-01	3.18E-01	4.66E-01	1.65E-01
	Sensitivity/Baseline	-19.62%	-26.12%	-25.55%	-12.10%	-25.73%	-25.28%	-27.32%	-17.49%
Metal depletion	kg Fe eq	2.64E+00	2.23E+00	5.24E-02	6.67E-01	2.35E+00	2.34E+00	2.67E+00	2.27E+00
	Sensitivity/Baseline	0.43%	-1.53%	658.22%	7.08%	-1.49%	-1.23%	-2.81%	0.99%
Fossil depletion	kg oil eq	1.09E+01	1.14E+01	9.82E-02	1.30E+00	1.26E+01	1.24E+01	1.44E+01	1.03E+01
	Sensitivity/Baseline	-4.70%	-9.76%	-6.86%	-2.81%	-9.06%	-8.52%	-11.60%	-3.48%

The substitution of nets and the consequent potential reduction in harvesting time have much more pronounced effects when using the functional units of surface (1ha) and mass (1kg).

In fact, the reduction in operating time translates into less time to harvest the production in one hectare and, therefore, less time to harvest the product unit, thanks to the reduction in operating time. The effects, therefore, have repercussions on all the inputs and outputs considered in the inventory

(Tables 15 and 16), and effects in terms of ecoprofile (Figure 10 and 11) presented at the endpoint level are comparable with the results shown previously.

Table 15 - Environmental Life Cycle Inventory for sensitivity analysis (FU 1ha of olive grove harvested)

Scenario	Agricultural Machinery	Agricultural Equipment	Diesel	Shed	Lubricant	Net
	kg ha^{-1}	kg ha^{-1}	l ha^{-1}	m^2 ha^{-1}	kg ha^{-1}	m^2 ha^{-1}
I	5.78	0.69	53.84	0.01	0.20	38.50
II	1.96	0.30	22.12	0.00	0.20	38.50
III		2.23				38.50
IV	13.13	2.25	46.31	0.10	0.02	38.50
V	2.12	0.24	24.80	0.00	0.21	38.50
VI	2.30	0.26	26.99	0.00	0.21	38.50
VII	1.59	0.16	17.15	0.00	0.21	38.50
VIII	6.94	0.98	76.40	0.01	0.20	38.50

Table 16 - Environmental Life Cycle Inventory for sensitivity analysis (FU 1kg of harvested olives)

Scenario	Agricultural Machinery	Agricultural Equipment	Diesel	Shed	Lubricant	Net
	kg kg^{-1}	kg kg^{-1}	l kg^{-1}	m^2 kg^{-1}	kg kg^{-1}	m^2 kg^{-1}
I	7.07E-04	8.42E-05	6.59E-03	1.23E-06	2.45E-05	4.71E-03
II	1.89E-04	2.92E-05	2.13E-03	4.29E-07	1.93E-05	3.71E-03
III	0.00E+00	3.35E-04	0.00E+00	0.00E+00	0.00E+00	5.78E-03
IV	2.33E-03	4.00E-04	8.22E-03	1.74E-05	3.55E-06	6.83E-03
V	3.93E-04	4.45E-05	4.59E-03	8.16E-07	3.89E-05	7.13E-03
VI	3.66E-04	4.14E-05	4.30E-03	7.60E-07	3.34E-05	6.13E-03
VII	4.20E-04	4.23E-05	4.53E-03	8.47E-07	5.55E-05	1.02E-02
VIII	5.21E-04	7.37E-05	5.73E-03	1.08E-06	1.50E-05	2.89E-03

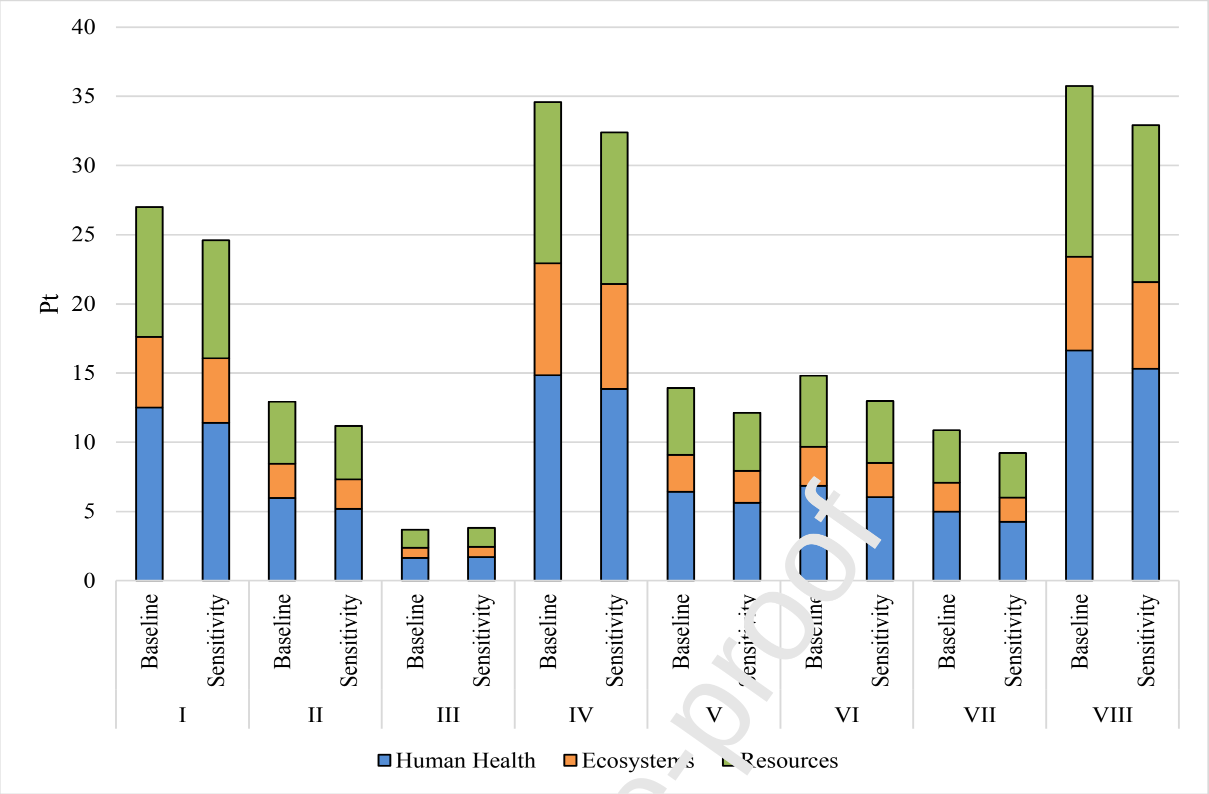


Figure 10. *Sensitivity vs Baseline scenario at endpoint level (FU 1 ha of olive grove harvested).*

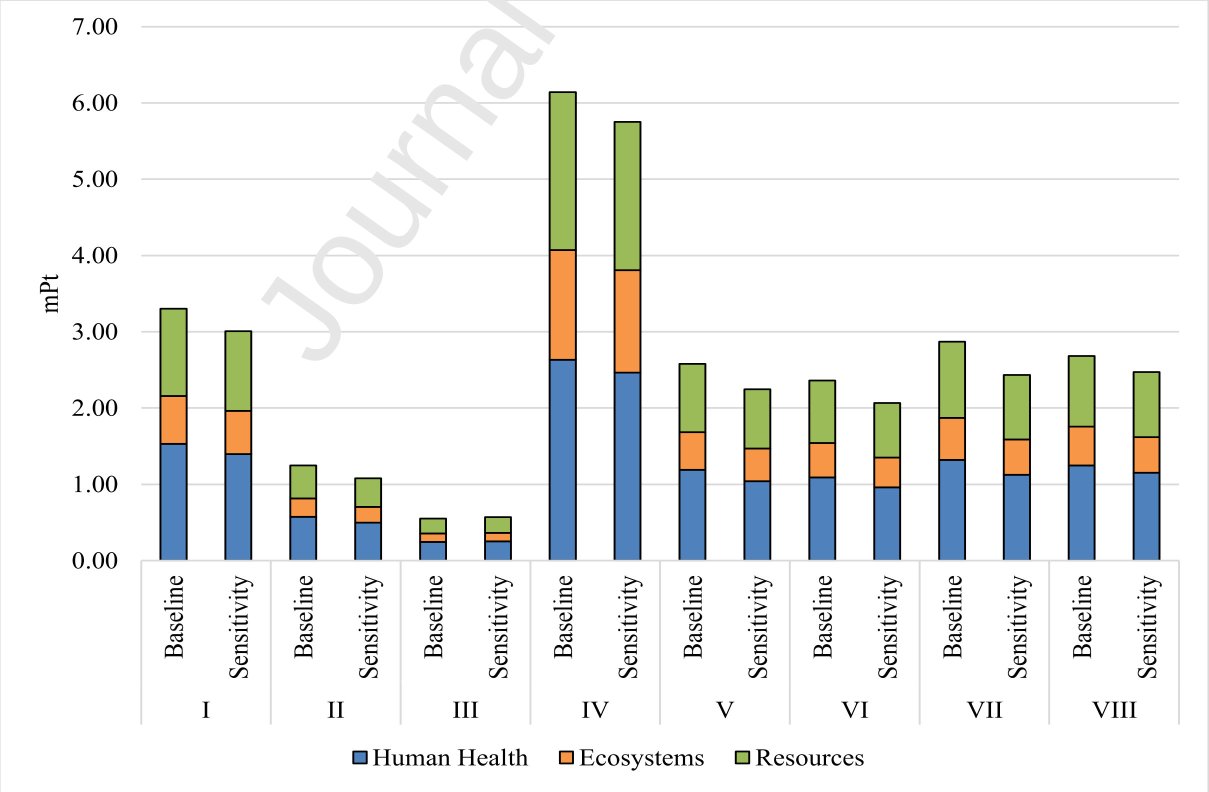


Figure 11. *Sensitivity vs Baseline scenario at endpoint level (FU 1 kg of olive harvested).*

Considering all the three functional units, scenario III is the only one that suffers a worsening of environmental impacts due to the use of agricultural equipment.

The number of scenarios could be a limitation of this study, but there is to say that a more large perspective would have required an increase in the commitment of resources. Therefore, it was preferred to limit the analysis to scenarios that more than others characterises Mediterranean olive growing from a technical-agronomic point of view.

In addition, to better understand the impacts of human labour on the overall sustainability of the process, the integration of some social aspects in this type of analysis could be helpful. This limitation could be overcome through the implementation of an *ad-hoc* Social Life Cycle Assessment (sLCA) analysis (Iofrida et al., 2019; Iofrida et al., 2018; De Luca et al., 2015), carried out consistently with the assumptions of the other life cycle-based approaches, and supported by the availability of specific data on different and valuable scenarios useful to be applied. However, given the boundaries of the system limited to the unitary process, it would be difficult to obtain significant results. Furthermore, a stand-alone social analysis in its own right would not be sufficient. Indeed, in order to make very effective and meaningful an overall sustainability analysis, a Life Cycle Sustainability Assessment (LCSA) (Klöpffer, 2008) should be added beyond, to take into account environmental, economic and social constraints, from the same life cycle point of view, also in order to understand how impacts can shift among life cycle phases and which hotspots occur. To date, LCSA is not yet standardized, furthermore, its application must also be strengthened by other decision support tools, as for example multicriteria methodologies, to assess the different sustainability dimensions (criteria and indicators) that, due to their multifaceted features generates a greater complexity of the system (De Luca et al., 2018). All that goes far beyond the aims of this study; therefore, it was decided to include some social considerations that do not claim to replace a more comprehensive analysis; in particular, following some published results, it is possible to get an idea of what the impacts related to human labour might be. De Luca et al. (2018) have published the working conditions with health risks, some of which may be associated with the collection operation.

Mechanical harvesting scenarios can be associated with Noise and Total Boby Vibrations with potential upper limb risk (Stock et al., 2006) and Sciatic Pain, Back Pain, Neck and Shoulders (Bovenzi and Betta, 1994; Stock et al., 2006).

Mechanically aided harvesting scenario can be associated with Noise, Vibration manual tools (Small hand-held shaker), High physical demand (Bernardi et al. 2020) and Heavy manual labour. The problems associated with these risks are musculoskeletal diseases of the upper limbs (Bernardi et al., 2018; Stock et al., 2006), Back Pain, Neck and Shoulders (Bovenzi and Betta, 1994; Stock et al., 2006) and Osteoarthritis (Zarz and Larkin, 2011).

Manual harvesting scenario may be associated with the risks of High physical demand, Temporary employment, Heavy manual labour, Work pressure, Effort-reward imbalance with potential health repercussions in terms of: Cardiovascular disease (Siegrist 1996), Back Pain (Raeisi et al., 2014; Domenighetti et al., 1999), Neck and Shoulders (Stock et al. 2006), Upper Limbs (Callea et al. 2014; Stock et al. 2006;), Lower self esteem (Domenighetti et al., 1999), High level of stress perceived (Domenighetti et al., 1999), Disability (Lahelma, 2012) and Osteoarthritis (Zarz and Larkin, 2011).

4. Overall assessment

Summarising the assessment results considering as a FU one hour of harvesting operation (Table 17), the emerging framework was heterogeneous. Sites III and IV had better environmental and economic performance. However, the mechanised system obtained a better performance in terms of working capacity but a worse performance for environmental and economic indicators. These results are attributable to the consumption of diesel from an environmental point of view and to the fixed cost used for the economic analysis.

Table 17. *Summary performance assessment (FU 1 h of harvesting).*

Scenario	Work capacity	Environmental impact	Total Hourly Cost
	kg h^{-1}	pt h^{-1}	€ h^{-1}
I	1,175.32	3.88	61.11
II	3,386.61	4.22	73.61
III	59.12	0.03	26.09
IV	83.21	0.51	31.52
V	1,779.12	4.59	93.45
VI	1910.13	4.51	96.16
VII	1870.12	5.37	97.90
VIII	1342.33	3.60	82.89

To better compare the results from the technical, economic, and environmental assessments, the results per hour of harvesting were normalised. The working capacity results were minimised so that for all three issues assessed the lowest value represented the best scenario and the highest value represented the worst one (Fig. 12). The normalised score obtained by the single scenario for each one of the three aspects analysed were summed to obtain an overall score (Fig. 13)

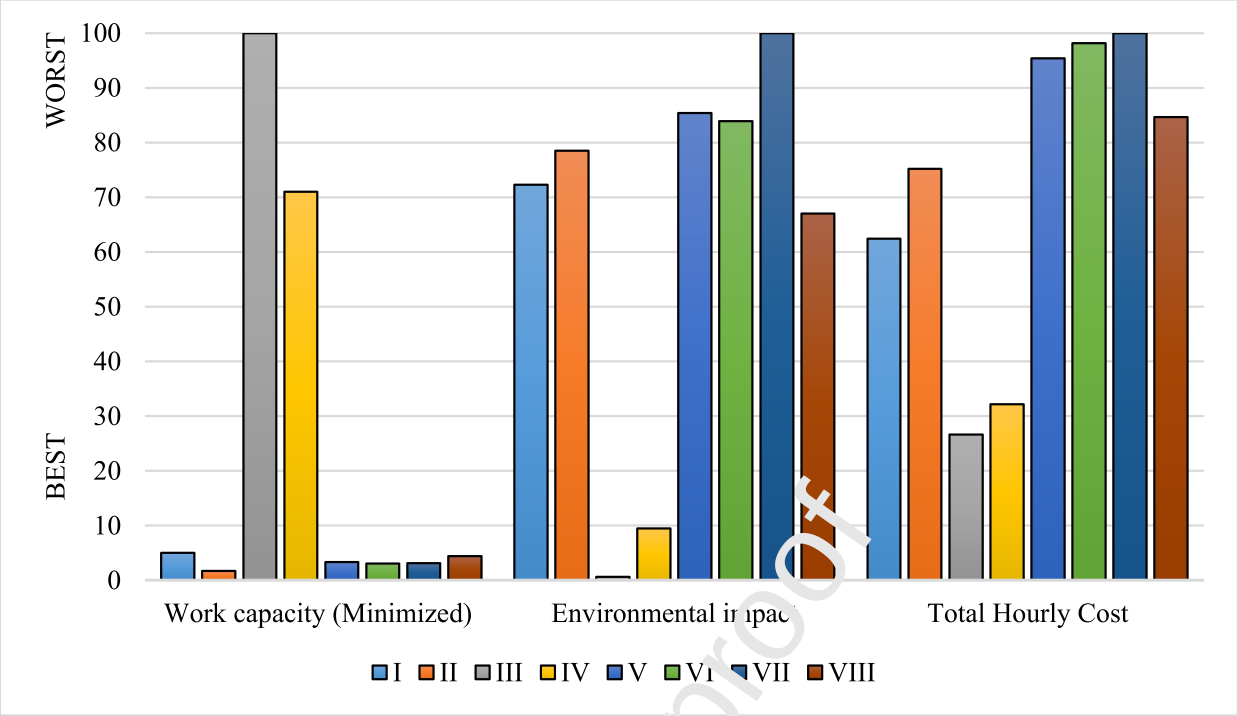


Figure 12. *Normalised performance assessment (FU 1 h of harvesting).*

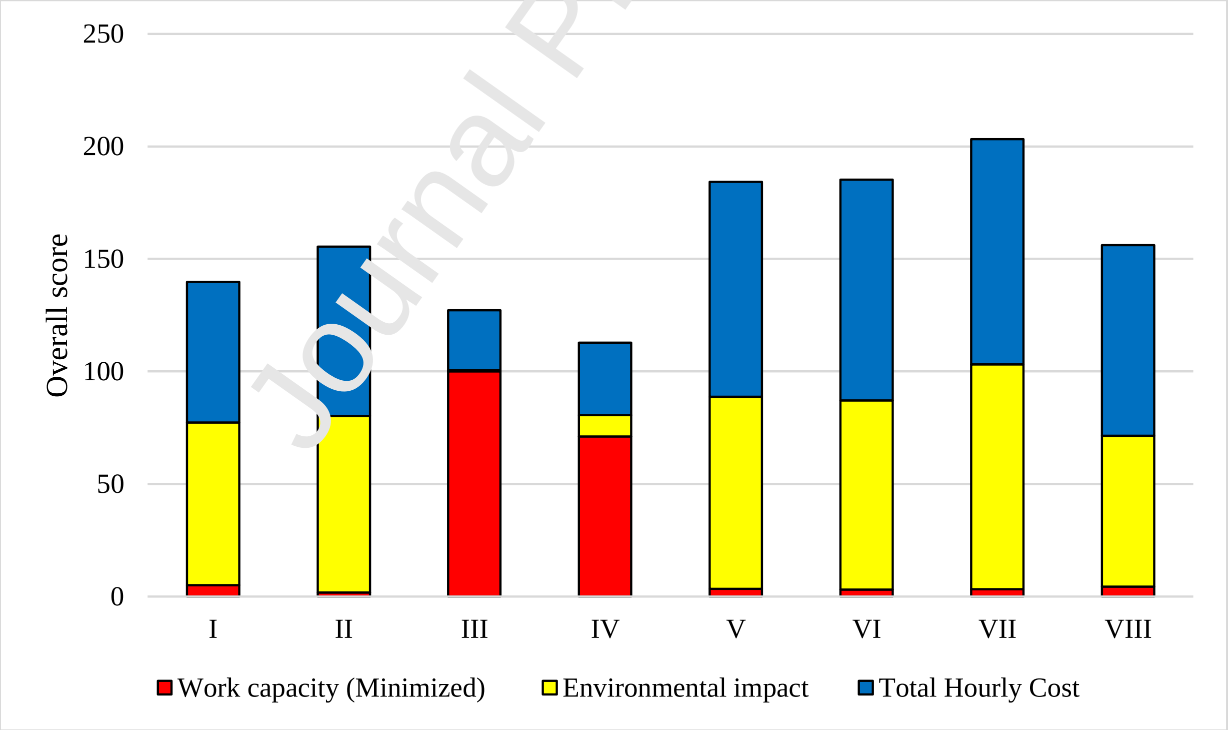


Figure 13. *Overall performance assessment (FU 1 h of harvesting)*

Sites III and IV had the best performance owing to lower environmental impacts and hourly costs. Even if the working capacity had been the highest influence at these two sites, the use of hour of harvesting as the FU allowed these two sites to obtain the best results. The mechanical harvesting solution showed a similar profile; therefore, the choice of what type of system is operationally better depends mainly on the technical choice.

4. Conclusions

The determination of the most suitable harvesting system was not a simple calculation owing to the heterogeneity of the studied harvesting sites, which reflect the real contexts of olive cultivation in Calabria and which largely represent the possible harvesting scenarios that can be identified in Mediterranean olive growing. If the use of machinery, nowadays supported by the availability of low-cost technology, is one of the focal points thanks to which the olive oil sector can be enhanced, technical (eg. high slopes, root system too weak for the use of machines) and technological (eg. low use of mechanization in some areas of the Mediterranean) problems still make the use of manual harvesting or assisted harvesting by hand-held machines widespread.

Technical, economic and environmental analysis allowed to trace the profiles of the different harvesting scenarios, which can be used as a decision support for the choice of the best technique to adopt, as a support tool for the management planning of the farm and as a support for the environmental analysis of olive life cycle, thanks to specific data and results related to harvesting operations, which unlike other agricultural operations, is absent in the main commercial databases.

The use of the modular LCA approach allowed, in fact, the enrichment of a ready-to-use and scalable database related to harvesting operation. The modular approach was an efficient solution for the determination of specific databases related to complex unitary operations. This method is easily exportable to other unitary operations, even those that are not related to agricultural production processes. The enrichment of specific datasets can ensure an increasing robustness of

LCA studies, which are often based on secondary data and, in the absence of process-specific models, modelled based on substitute processes

LCA practitioners can use the findings of the modular assessment from the present study for studies on olive growing, customising the results to their specific needs as achieved in the present study using scaling methods.

The determination of the most suitable harvesting system is complex and there is a need for a precise analysis of all the features that characterise an orchard. It is not possible to define the best harvesting solution overall but rather the best harvesting solution for a specific production context can be determined.

The mechanisation of harvesting operations, therefore, remains a priority objective. This can only result from a multidisciplinary approach, involving not only engineering competences, but also arboricultural skills, food technology, and entrepreneurial factors. This is made in the wake of an agriculture that requires greater precision, data sharing, rapid availability of timely information, and communication not only between machines, but also among the different protagonists of the supply chain; the one that today many people call “agriculture 4.0”.

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CREDIT AUTHOR STATEMENT

Bruno Bernardi: Conceptualization; Investigation; Formal analysis; Writing - Original Draft, Review & Editing of abstract and chapters 1-2-2.1-2.2-2.3-3-3.1-5; Supervision; Resources; Project administration.

Giacomo Falcone: Conceptualization; Investigation; Formal analysis; Writing - Writing - Original Draft, Review & Editing of abstract and chapters 1-2-2.5-3-3.3-4-5.

Teodora Stillitano: Conceptualization; Investigation; Formal analysis; Writing - Writing - Original Draft, Review & Editing of abstract and chapters 1-2-2.4-3-3.2-5.

Souraya Benalia: Conceptualization; Investigation; Formal analysis; Writing - Original Draft, Review & Editing of abstract and chapters 1-2-2.1-2.2-2.3-3-3.1-5.

Jacopo Bacenetti: Conceptualization; Writing Original Draft, Review & Editing of chapters 1-2-2.5-3-3.3-4-5.

Anna Irene De Luca: Conceptualization; Review & Editing of chapters 1-2-2.4-2.5-3-3.3-3.3-4-5; Supervision.

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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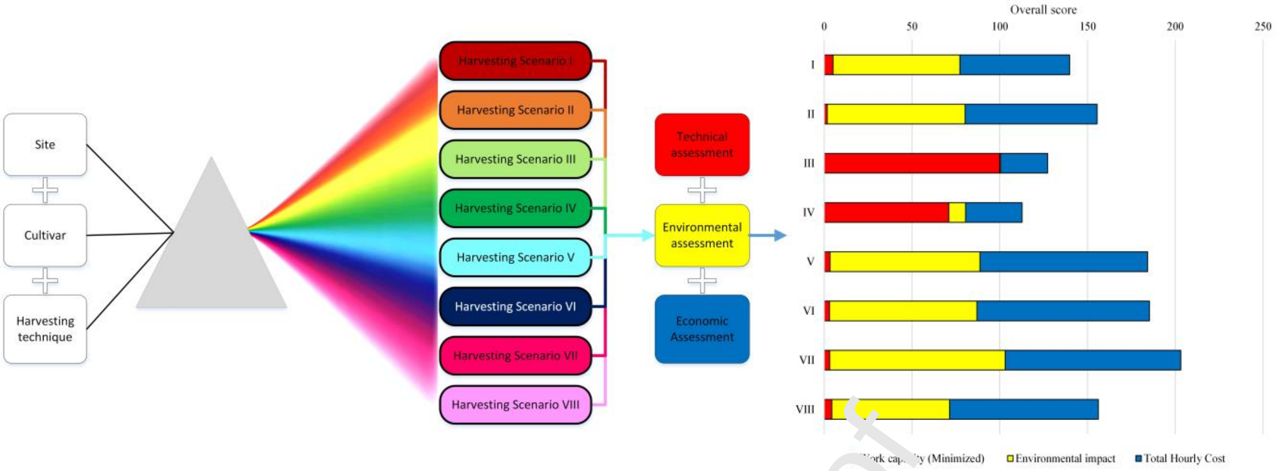

Graphical abstract

Highlights

- Harvesting sites of the main spread olive varieties in Calabria have been analysed
- Mechanical harevesting is the only way to rise productivity and reduce production costs
- Results related to environmental impact of harvesting operations depend on the assumed FU
- “Mass based FU” could be considered as the most representative for LCA of olive and olive oil production
- Modular LCA approach allowed the enrichment of harvesting operation database